Transmission Capacity Improvement Using Unified Power Flow Controller with New Control Strategy

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***Abstract*—This paper presents Unified Power Flow Controller (UPFC) with a new control strategy to improve the transmission capacity in power system network. With the growing demand of electricity, it is not possible to erect new lines to face the situation. Therefore UPFC is optimally utilizes to enhance the existing transmission network. A detail explanation of the controllers for both shunt and series converters of UPFC and DC link capacitor rating are presented in this study. To justify the performance of the UPFC model, 230kV transmission system in Upper Myanmar National Grid is considered as case study. The proposed control system performance is checked by applying different faults across a transmission line to which UPFC is connected. This is necessary because of the chance for occurance of fault is larger for this case study network. And, loading condition is changed to study the control system response. The simulation results show the effectiveness and suitable performance of the control strategy at improving transmission capacity. Transmission network model and all simulations have been done using MATLAB/Simulink software.**

***Index Terms*—Unified power flow controller, new control strategy, transmission line capacity, control system response**

I. Introduction

With the increased electrical power demands, competitive situation in the electric market is increasing day by day, thereby pressing transmission lines due to inadequate sources of energy [1]. Since electrical energy is essential for a country's development, therefore there is an unending demand for this energy [2]. As a result, the stressed power systems face the problem of stability, security, economic and reliability for power supply [3]. It is not possible to build a new transmission line because it is constrained by huge rising cost, environmental impact and long construction time. Therefore existing networks need to be optimized to transmit more power during both normal and abnormal conditions [4]-[7]. Flexible Alternating Current Transmission Systems (FACTS) devices enhance power transfer capacity of the line without adding new transmission line [8]. This is necessary because of the increase in load growth with every passing day without an equivalent increase of line capacity [9].

FACTS devices are power electronic-based controllers to enhance controllability and increase power transfer capability [10], [11]. The FACTS Devices improve the transient stability by reducing the reactance of lines and also increase the power flow capacity of transmission lines [12]. The unified power flow controller (UPFC), one of FACTS devices, was proposed by L. Gyugyi in 1991 [13], [14]. The UPFC combines the functions of static synchronous compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) and capable of implementing voltage regulation, series compensation, and phase angle regulation at the same time. Thus it can simultaneously control active and reactive power transmitted over the line [15]. UPFC can also improve the voltage profile and reduce power loss of transmission network [16]. FACTS and voltage-source converters, with smart dynamic controllers, are emerging as a stabilization and power filtering equipment to improve the power quality [17]. References [18] and [19] presented the surveys of the UPFC model for steady-state and transient state. In the area of power flow analysis, UPFC models have been published [20], [21]-[25] which had two voltage source converters, one is shunt converter and another is series converter. The modular multilevel converter-based UPFC also regulates the power flow of the power system in both steady state and transient state conditions [26].

To study the performance of the UPFC, a de-coupled control system has been designed for the shunt inverter to control the UPFC bus voltage and the DC link capacitor voltage. The series inverter of a UPFC controls the real power flow in the transmission line. Further, in order to facilitate proper operation between the series and the shunt inverter control system, a new real power coordination controller has been developed. The other problem concerning the operation of a UPFC is with respect to transmission line reactive power flow control. Step changes to transmission line reactive power references have significant impact on the UPFC bus voltage. To reduce the adverse effect of step changes in transmission line reactive power references on the UPFC bus voltage, a new reactive power coordination controller

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has been designed. Finally, a new control strategy has been proposed for UPFC. In this proposed control strategy, the shunt inverter controls the DC link capacitor voltage and the transmission line reactive power flow. The series inverter controls the transmission line real power flow and the UPFC bus voltage.

The work involved in this paper is concentrated on modeling of UPFC and a new decoupled based control strategy. Experimental works have been conducted to verify the improvement of transmission system performance by using UPFC with new control strategy. Modeling is done by using MATLAB/SIMULINK software. The case study is carried out for 230kV transmission system in Upper Myanmar National Grid. Due to the switching of power electronic switches in shunt and series converter, some harmonic distortion may be observed in the transmission system. In this study, the transmission capacity improvement is emphasized and thus the harmonic content is not considered in detail.

II. NEW CONTROL STRATEGY OF UPFC

A new control strategy has been proposed to achieve simultaneous control of four variables namely, transmission line real power flow (P_{line}), transmission line reactive power (Q_{line}), UPFC bus voltage (V_{upfcbus}) and the DC link capacitor voltage (V_{dc}). To understand the proposed control strategy, consider a UPFC connected to a transmission line as shown in Fig. 1. In the proposed strategy, the series inverter of a UPFC controls the real power flow in the transmission line (P_{line}) and the UPFC bus voltage (V_{upfcbus}) the shunt inverter of the UPFC controls the transmission line reactive power (Q_{line}) and the DC link capacitor voltage (V_{dc}).

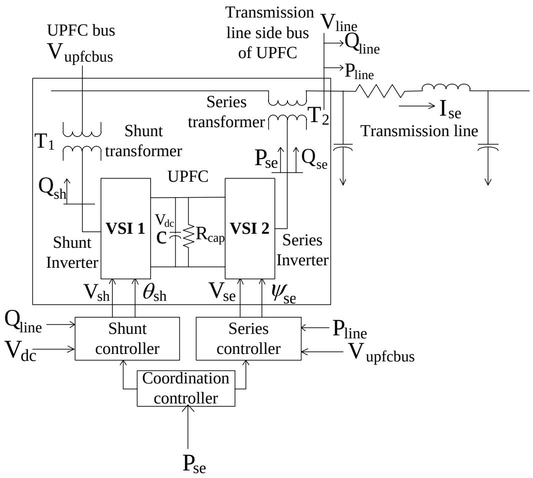

Fig. 1. UPFC connected to a transmission line.

To achieve this type of control strategy for UPFC, the series inverter injected voltage is split into two components, one in-phase and the other in quadrature with the UPFC bus voltage. The quadrature component of the series injected voltage (V_{seQ}) controls the real power flow in the transmission line (P_{line}) and the in-phase component of the series injected voltage (V_{seD}) controls the UPFC bus voltage (V_{upfcbus}).

The advantage with this strategy is that by controlling the transmission line reactive power flow directly by the shunt inverter, the need for reactive power coordination controller is eliminated. Therefore, the shunt inverter can be used to manufacture and export required quantity of reactive power to the transmission line. MATLAB simulations have been performed to show the validity of the proposed control strategy and to show the transmission capacity improvement.

A. Shunt Inverter Control System

The shunt inverter is controlled using the decoupled control system. Fig. 2 shows the shunt inverter control system with the real power coordination controller. In the proposed strategy, the shunt inverter controls the transmission line reactive power flow (Q_{line}) and the DC link voltage (V_{dc}).

$$V_{\text{shD}} = V_{\text{upfc}} + \frac{\omega_0}{L_{\text{sh}}}\left(u_1 - \omega\omega_0 I_{\text{shQ}}\right) \tag{1}$$

$$V_{\text{shQ}} = \frac{\omega_0}{L_{\text{sh}}}\left(u_2 - \omega\omega_0 I_{\text{shD}}\right) \tag{2}$$

$$u_1 = \left(K_{p1} + \frac{K_{i1}}{S}\right)\left(I_{\text{shDref}} - I_{\text{shD}}\right) \tag{3}$$

$$u_2 = \left(K_{p2} + \frac{K_{i2}}{S}\right)\left(I_{\text{shQref}} - I_{\text{shQ}}\right) \tag{4}$$

$$I_{\text{shDref}} = \left(K_{p3} + \frac{K_{i3}}{S}\right)\left(V_{\text{dcref}} - V_{\text{dc}}\right) \tag{5}$$

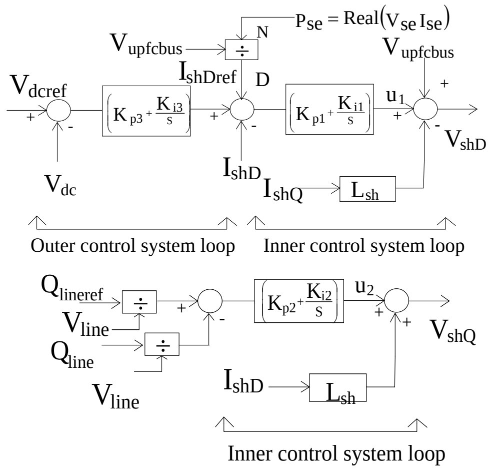

Fig. 2. Shunt inverter control system with real power coordination controller.

The transmission line reactive power (Q_{line}) is controlled by the Q-axis shunt inverter voltage (V_{shQ}). The DC link capacitor voltage (V_{dc}) is controlled by the D-axis shunt inverter voltage (V_{shD}). The PI controller gains are used for the shunt inverter controller.

B. Series Inverter Control System

The series inverter injected voltage is split into two components, one in-phase (V_{seD}) and the other in quadrature (V_{seQ}) with the UPFC bus voltage. The series inverter controls the real power flow in the transmission line (P_{line}) by injecting a voltage in quadrature (V_{seQ}) with the UPFC bus voltage (V_{upfcbus}). The in-phase component (V_{seD}) of the series injected voltage controls the UPFC bus voltage (V_{upfcbus}). Two PID controllers have been implemented to control the real power flow in the transmission line (P_{line}) and the UPFC bus voltage (V_{upfcbus}) shown in Fig. 3.

$$P_{\text{line}} = \left(\left|V_S\right| + V_{\text{seD}}\right) I_{\text{seD}} + V_{\text{seQ}} I_{\text{seQ}} \tag{6}$$

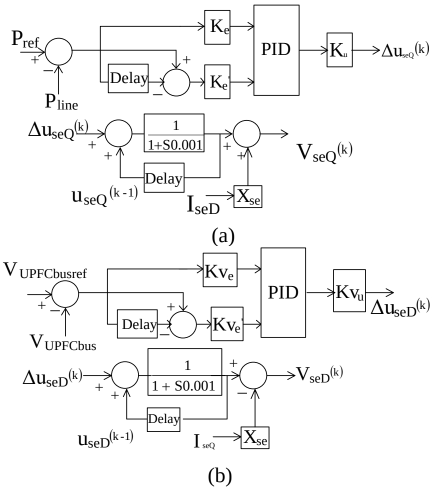

Fig. 3. Series inverter control system for new control strategy: (a) Transmission line real power flow controller and (b) UPFC bus voltage controller.

C. DC Link Capacitor Rating

It provides the necessary DC voltage for the operation of the shunt and the series inverters. In steady state, the shunt inverter supplied the real power demand of the series inverter. Transient state, the shunt inverter does not respond and causes the DC capacitor to charge/discharge to meet the real power demand of the series inverter. This leads to an increase/decrease of DC capacitor voltage (V_{dc}). Based on the amount of increase/decrease in V_{dc}, the DC capacitor has been designed.

$$W_c = \frac{1}{2} C \left(V_{\text{dcref}} - V_{\text{dc}}\right)^2 \tag{7}$$

The capacitance of the DC Capacitor is selected 2500μF.

D. Tuning of PID Controllers

PID Controllers are used in most of control due to its simplicity and excellent performance in many applications. They are used in more than 95% of closed-loop control processes. The parameters (K_P, K_I and K_D) can be tuned by operators without extensive background in controls. Most PID controllers are tuned on-site due to converter and process variations. The effects of increasing each of the controller parameters are summarized in Table I.

In modeling of UPFC controllers, the following controller gain parameters are applied.

For shunt inverter control system; inner loop controller; K_{p1}=0.005, K_{i1}=0.01, K_{p2}=0.1, K_{i2}=0.1, outer loop controller K_{p3}=0.0001, K_{i3}=0.01

For series inverter control system; Transmission line real power flow controller, K_p=0.1, K_i=20, UPFC bus voltage controller K_p=0.015, K_i=25.

TABLE I: EFFECT OF INCREASING PARAMETER IN PID CONTROLLER

Parameter	Rise time	Overshoot	Settling time	Steady-state error
K_p	Decrease	Increase	Small change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
	Minor change	Decrease	Decrease	No effect in theory

The PI parameters are tuned based on Table I until the responses of series DC controller, shunt DC controller and UPFC voltage signal are stable and acceptable for transmission capacity improvement.

III. ALLOCATION OF UPFC ON THE CASE STUDY NETWORK

A. Study on Upper Myanmar National Grid

In Myanmar Electric Power System, large transmission areas with large loads are studied with a view to making more reliable power system for continuity of supply. The input data for transmission system enhancement program represents the load and generation. Distribution circuits and small loads are not shown in detail because buses are taken account into merely as lumped loads on substation buses. The model of all networks, generators, transformers and shunt capacitors are selected depending on the optimum condition from data collection to solve and study for the problem of Transmission System. Myanmar Electric Power System is rather large for modeling since it consists of hundreds of buses and tens of generations consisting of hydro and thermal plants. Thus, the case study is carried out for part of Myanmar Electric Power System consisting of 230kV buses located in Upper Myanmar National Grid. The system under study consists of 12 numbers of 230kV buses, two hydro power stations and ten loads. The single line diagram is illustrated in Fig. 4.

To observe the performance of UPFC, the simulations are carried out with Simulink model as well as Matlab program. For these simulations, the input bus and line data for 12 numbers of 230kV buses system are expressed in the following Table II and Table III.

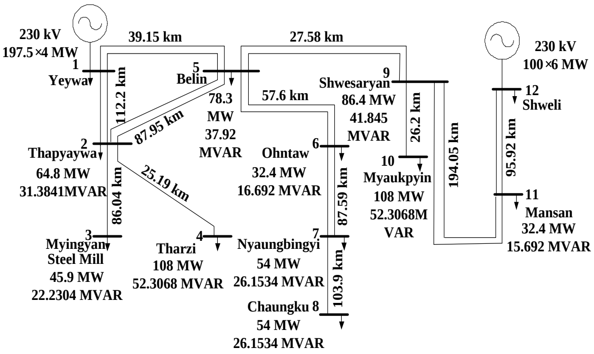

Fig. 4. Single line diagram for 230 kV system in upper Myanmar National Grid.

TABLE II: LINE DATA FOR 12 NUMBERS OF 230 KV BUSES SYSTEM IN UPPER MYANMAR NATIONAL GRID

Line Flow	*R* (pu)	*X* (pu)	1/2 *B* (pu)	Xmer Tap
1_2	0.008713	0.041475	0.1108721	1
1_5	0.0030402	0.014472	0.0386866	1
2_3	0.00836	0.03486	0.0813201	1
2_4	0.0024476	0.010206	0.0238082	1
2_5	0.0068298	0.032511	0.0869091	1
5_6	0.0055968	0.021845	0.0561576	1
5_9	0.0021418	0.010195	0.0272536	1
6_7	0.0085108	0.033219	0.0853967	1
7_8	0.0100954	0.042096	0.1000988	1
9_10	0.0025457	0.010615	0.0247628	1
9_11	0.0188551	0.073595	0.1927526	1
11_12	0.0093202	0.036379	0.0952707	1

TABLE III: BUS DATA FOR 12 NUMBERS OF 230 KV BUSES SYSTEM IN UPPER MYANMAR

Bus No	Bus Code	V_m (pu)	V_a	Load	
				P (MW)	*Q* (MVAR)
1	1	1	0	0	0
2	0	1	0	64.8	31.3841
3	0	1	0	45.9	22.2304
4	0	1	0	108	52.3068
5	0	1	0	78.3	37.9224
6	0	1	0	32.4	16.692
7	0	1	0	54	26.1534
8	0	1	0	54	26.1534
9	0	1	0	86.4	41.8454
10	0	1	0	108	52.3068
11	0	1	0	32.4	15.692
12	2	1	0	0	0

B. Location and Sizing of UPFC

In the determination of transmission line performance, the bus voltages, line flows and power losses are the critical factors. Thus the sizing and allocation of UPFC is done based on these data.

1) The sizing of UPFC select depend on the reactive power flow on this line.
2) The location of UPFC select depend on the bus voltage and line flow condition.

TABLE IV: SIMULATION RESULTS FOR 230 KV BUSES SYSTEM IN UPPER MYANMAR NATIONAL GRID WITHOUT UPFC

Bus No	*V* (kV)	*P* (MW)	*Q* (MVAR)
1	230	472.00	101.2
2	220	196.00	69.42
3	218	41.50	20.12
4	218	95.00	47.33
5	219	172.00	17.74
6	217	123.00	15.86
7	214	93.10	20.21
8	212	45.90	22.27
9	217	173.00	78.49
10	216	95.40	46.23
11	223	136.00	-0.661
12	225	137.00	-20.35

TABLE V: SIMULATION RESULTS FOR LINE FLOWS OF 230 KV BUSES SYSTEM IN UPPER MYANMAR NATIONAL GRID WITHOUT UPFC

Line Flow	MW	Mvar	MVA
1_2	113.74	104.758	154.63
1_5	66.065	395.347	400.83
2_3	46.124	8.862	46.97
2_4	108.398	49.77	119.28
2_5	-107.878	24.752	110.68
5_6	143.607	41.851	149.58
5_9	-269.673	334.683	429.81
6_7	109.762	29.252	113.59
7_8	54.421	12.009	55.73
9_10	108.445	50.10	119.46
9_11	-469.033	225.92	520.61
11_12	-569.506	-4.738	564.79

According to the simulation results, the voltages at bus 6, 7, 8, 9, and 10 are much lower than regulate value of 230kV is shown in Table IV. Therefore, these buses voltage can affect the voltage stability problem. The installation of UPFC must improve these bus voltages.

In the same way, the line flow on line 1-5, 5-9, 9-11 and 11-12 are much larger than the other lines as shown in Table V. The installation of UPFC must also reduce these line flows. To satisfy these conditions, the location of UPFC is selected at bus 9 on line 9-11.

For the sizing of UPFC, the reactive power at bus 9 and reactive power flow on line 9-11 is observed. According to simulation results, the reactive power of the buses between Shwesaryan and Mansan (L9_11) is 225.9 MVAR and the reactive power at bus 9 is 78.49 MVAR. For the optimal performance of selected 12 numbers of 230kV buses system, 100 MVAR shunt converter and 100 MVAR series converter is selected for the system.

IV. TRANSMISSION CAPACITY IMPROVEMENT USING UPFC WITH NEW CONTROL STRATEGY

For the improvement of transmission system performance, the selected UPFC is integrated to the 12 numbers of 230kV bus system in Upper Myanmar National Grid. The Simulink Model is shown in Fig. 5. For the simulation, the simulation time is set as 3 second and the sampling time is set as 0.5μs.

To analyze the transmission capacity improvement by UPFC, single line to ground fault (A-G fault) and three phase fault (A-B-C fault) are applied to the transmission lines. Since the fault closed to UPFC cause larger power flow on the UPFC integrated line i.e. line 11-9, the fault locations are selected on line 5-9 and line 9-10. To ensure the transmission line capacity improvement by UPFC, the line capacity is also calculated for without and with UPFC. The simulation results for various cases are obtained.

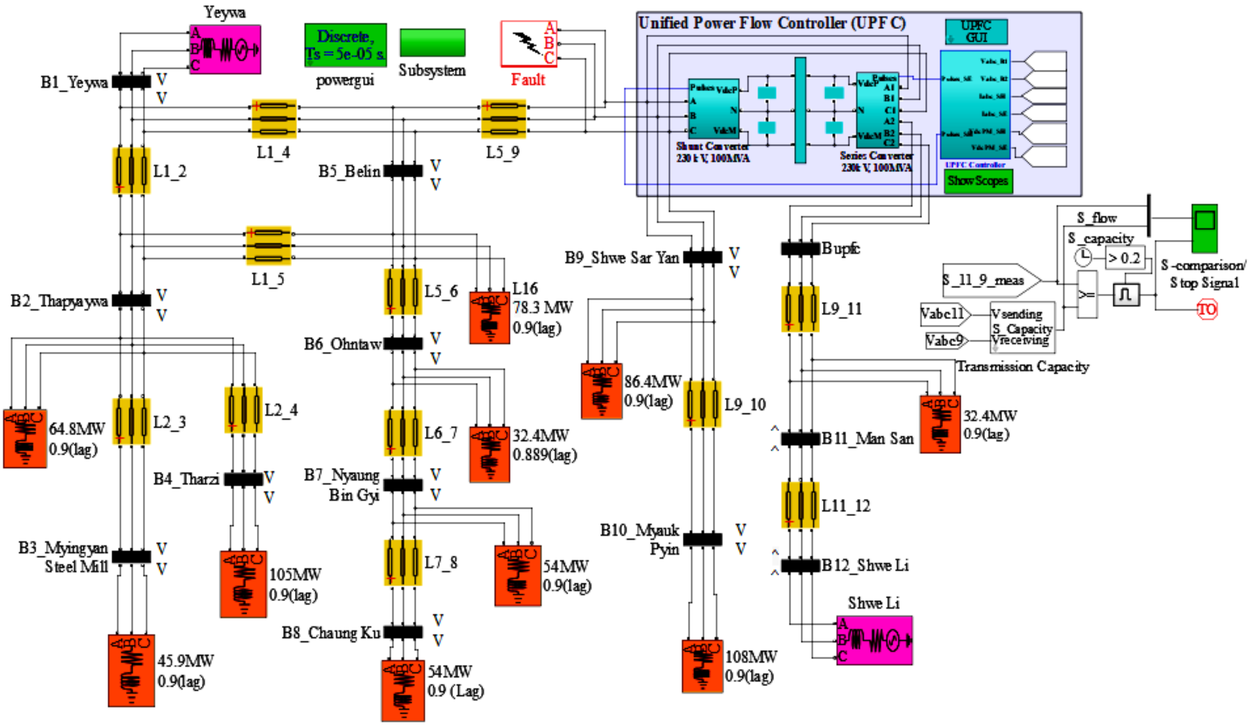

Fig. 5. Simulink model for 230kV system in Upper Myanmar National Grid with UPFC.

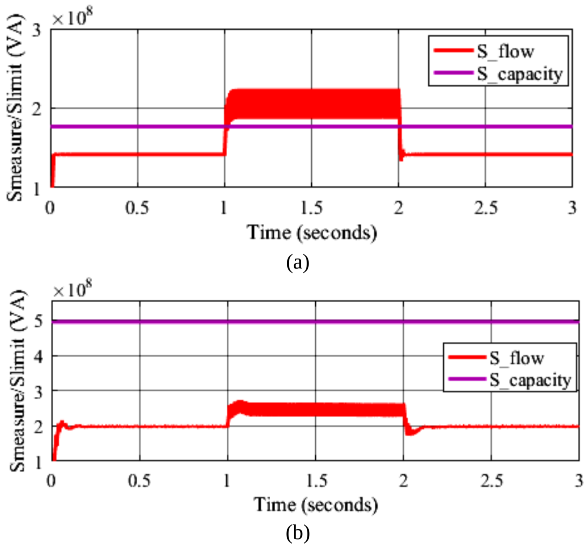

Fig. 6. Transmission line capacity and line flow for A-G fault on line 5-9: (a) Without UPFC and (b) With UPFC.

A. Single Line to Ground Fault on Line 5-9 at Bus 9 Side

In this case, A-G fault is applied on line 5-9 at bus 9 side. Simulations are carried out for with UPFC and without UPFC. The transmission line capacity and line flow are shown in Fig. 6.

Without UPFC, the transmission line capacity is about 187.1 MVA. With the application of UPFC, the transmission line capacity is improved to 494.4MVA. Thus, with the application of UPFC, the line capacity is improved by (494.4/187.1 = 2.64) 264 % compared to without UPFC case. Under normal condition, the power flow on line 9-11 is about 198.7MVA and this flow is within line capacity limits of without UPFC and with UPFC. During A-G fault, the power flow is increased to 260.2MVA. This flow is larger than the capacity of without UPFC case and thus the line can damage if it is not interrupted. With UPFC, the power flow during A-G fault is less than the line capacity; it can operate safely without interruption.

B. Three Phase Fault on Line 5-9 at Bus 9 Side

In this case, three phase fault is applied on line 5-9 at bus 9 side. Simulations are carried out for with UPFC and without UPFC. The transmission line capacity and line flow are shown in Fig. 7.

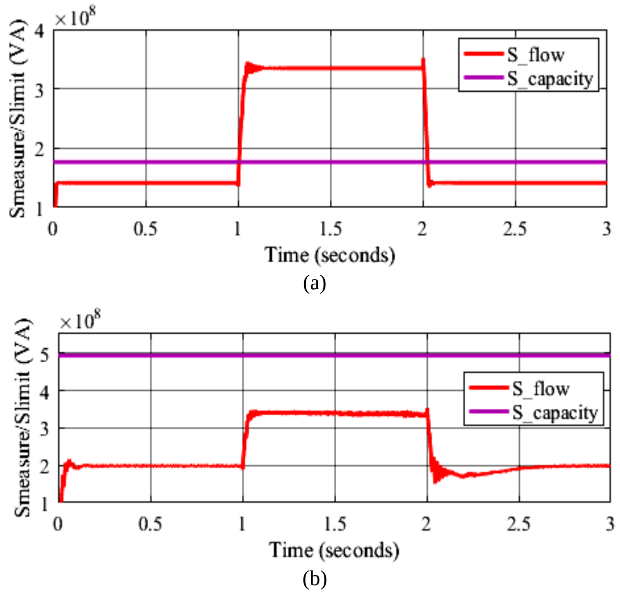

Fig. 7. Transmission line capacity and line flow for three phase fault on line 5-9: (a) Without UPFC and (b) With UPFC.

The transmission line capacities for without UPFC and with UPFC are same as in case ‘A’. Under normal condition, the power flow on line 9-11 is about 198.1 MVA and this flow is within line capacity limits of without UPFC and with UPFC. During three phase fault, the power flow is increased to 342.1MVA. This flow is much larger than the capacity of without UPFC case and thus the line can severely damage if it is not interrupted. With UPFC, the power flow during three phase fault is less than the line capacity; it can operate safely without interruption.

C. Single Line to Ground Fault on Line 9-10 at Bus 9 Side

In this case, single line to ground fault is applied on line 9-10 at bus 9 side. Simulations are carried out for with UPFC and without UPFC. The transmission line capacity and line flow are shown in Fig. 8. The transmission line capacities for without UPFC and with UPFC are same as in case 'A'. Under normal condition, the power flow on line 9-11 is still about 198.5MVA and this flow is within line capacity limits of without UPFC and with UPFC. During A-G fault, the power flow is increased to 260.2MVA. This flow is larger than the capacity of without UPFC case and thus the line can damage if it is not interrupted. With UPFC, the power flow during three phase fault is less than the line capacity; it can operate safely without interruption.

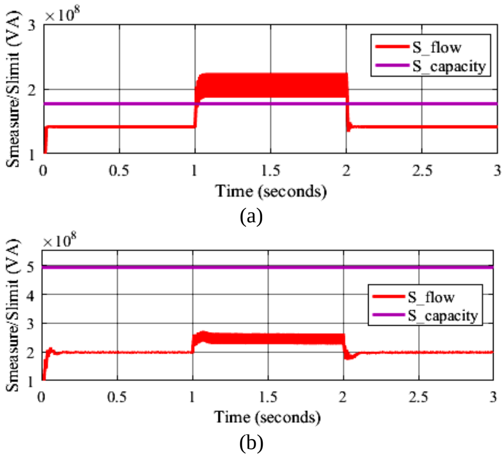

Fig. 8. Transmission line capacity and line flow for A-G fault on line 9-10: (a) Without UPFC and (b) With UPFC.

D. Three Phase Fault on Line 9-10 at Bus 9 Side

In this case, three phase fault is applied on line 9-10 at bus 9 side. Simulations are carried out for with UPFC and without UPFC. The transmission line capacity and line flow are shown in Fig. 9. The transmission line capacities for without UPFC and with UPFC are same as in case 'A'. Under normal condition, the power flow on line 9-11 is about 198.5MVA and this flow is within line capacity limits of without UPFC and with UPFC. During three phase fault, the power flow is increased to 340.4MVA. This flow is much larger than the capacity of without UPFC case and thus the line can severely damage if it is not interrupted. With UPFC, the power flow during three phase fault is less than the line capacity; it can operate safely without interruption.

Transmission line capacities and line flows comparison for without UPFC and with UPFC is illustrated in Fig. 10. As shown in Figure, line flow capacity of line 9-11 with UPFC is much higher than without UPFC case. Thus the line 9-11 must be interrupted for different faults in the system. Therefore the application of UPFC on line 9-11 can improve the line flow capacity to operate under fault condition.

The benefits from the use of FACTS devices are many; however, not all are tangible. Similarly, the costs of FACTS devices are also huge. From this, it is clear how expensive these technologies are. But, the cost has to compute against anticipated benefits. Financial benefit from FACTS devices comes from the additional sales due to increased transmission capability, additional wheeling charges due to increased transmission capability and due to delay in investment of high voltage transmission lines or even new power generation facilities. Also, in a deregulated market, the improved stability in a power system substantially reduces the risk for forced outages, thus reducing risks of cost revenue and penalties from power contracts. Considering the case study network, UPFC installation at the receiving end of line 9-11, the annual capital cost of UPFC is 121661 $/year. The annual revenue generated due to UPFC is 108500 $/year. Consequently, about US$ 13161 can be saved each year [27], [28].

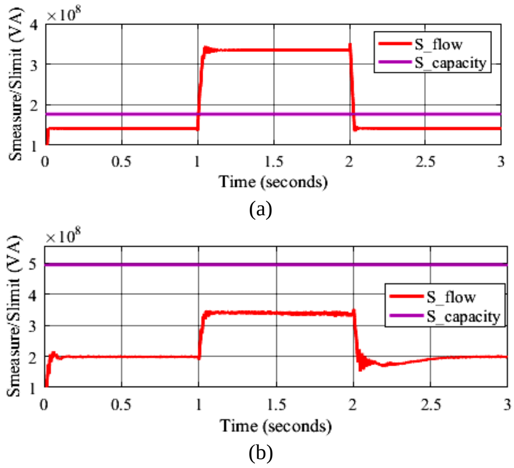

Fig. 9. Transmission line capacity and line flow for three phase fault on line 9-10: (a) Without UPFC and (b) With UPFC.

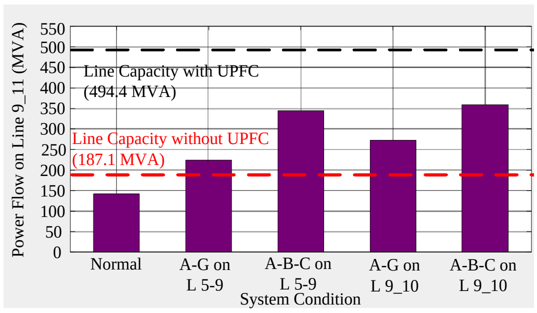

Fig. 10. Transmission line capacities and line flows comparison for without UPFC and with UPFC.

V. Control System Response for Load Change Condition

In this case, the load change is carried out at bus 11 (Mansan Bus). The load at this bus is originally 32.4MW with 0.9 power factor lagging. For the load change, the same load is added at 2 second. The simulation results are shown in Fig. 11 through Fig. 14. For each study, Q_{ref} signal, series controller signal, shunt controller signal, and UPFC signal response are observed.

Fig. 11 shows change in Q_{ref} signal due to load change. Before load change, Q_{ref} value is about -0.95 per unit and this value is decreased to -0.985 per unit. With this Q_{ref} value, the system can maintain system stability.

Fig. 12 shows signal response of series DC controller during load changes. The series controller voltage is about 21.1kV before load change. At the instant of load change, this voltage is drop to 20.9kV shortly. But this value reaches again to before load change value within millisecond range and maintains system stability.

Fig. 13 shows signal response of shunt DC controller during load changes. The shunt controller voltage is about 21.1kV before load change. It is the same as series controller voltage. At the instant of load change, the shunt controller voltage is drop to 20.87kV shortly. But this value reaches again to before load change value within millisecond range and maintains system stability.

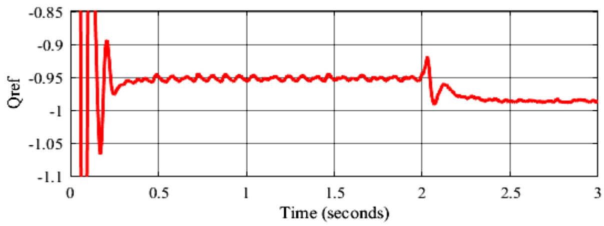

Fig. 11. Change in Q_{ref} signal.

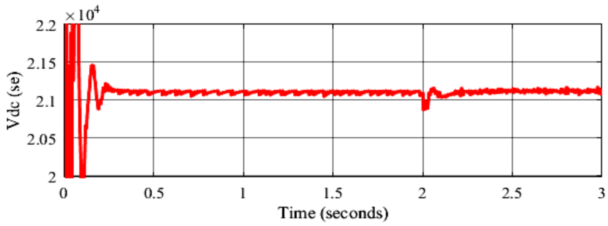

Fig. 12. Signal response of series DC controller during load changes.

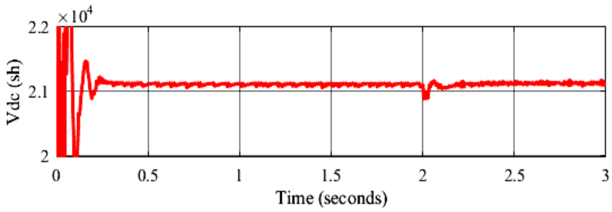

Fig. 13. Signal response of shunt DC controller during load changes.

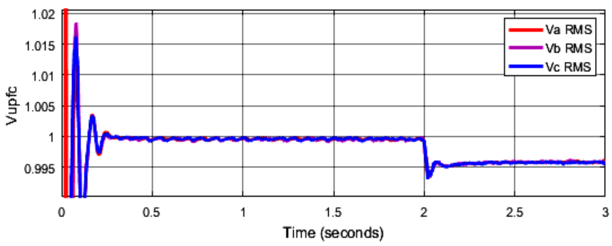

Fig. 14. Signal response of UPFC voltage during load changes.

Signal response of UPFC voltage during load changes is described in Fig. 14. UPFC voltage is 1 per unit before load change. When the load is added, the UPFC voltage is slightly reduced and stable at 0.996 per unit. All three phase voltage magnitudes of UPFC are identical for all load conditions.

VI. Conclusion

In this paper includes a complete new control system design for UPFC and studying its Transmission capacity improvement. In this study, the line can operate safely under normal condition. But the line flow will exceed the line capacity under fault conditions if UPFC is not utilized. With UPFC application, the transmission capacity is sufficiently higher than the line flow for different fault types in the system. Thus it can operate under system fault without interruption. Therefore the application of UPFC can improve the line flow capacity to operate under fault condition. In this research, the control signal response for load change is studied. The reference reactive power changes, shunt and series DC controller response signals and UPFC voltages are observed. According to the simulation results, the control signal response is fast and accurate to maintain the system stability. In conclusion, the work in this paper provides some fundamental models and methods to effectively investigate the UPFC and evaluate its impacts on transmission systems. They have been tested by some practical system data, which has proved them to be very effective and practical. The system planners and operators can use these theories and tools to solve problems which they will certainly encounter in the practical system. All the work done assume that the system is balanced. For further study, UPFC will operate reliably under unbalanced power system conditions with the new design of a control system.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Both authors conducted the research. The first author wrote the paper and both authors had approved the final version.

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